

# $\mathcal{P}$ -Odd Pion Azimuthal Charge Correlations at LHC

Yachao Qian<sup>1</sup> and Ismail Zahed<sup>1</sup>

<sup>1</sup>*Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800.*

We argue that the instanton induced  $\mathcal{P}$ -odd contributions to the Sivers effects in polarized proton-proton scattering, may cause substantial charge-dependent azimuthal correlations for  $\pi^\pm$  production in *unpolarized* proton-proton scattering at the LHC. We suggest that this mechanism may still be substantial in peripheral heavy ion collisions both at RHIC and LHC.

**1. Introduction.** A large Single Spin Asymmetry (SSA) in dedicated Semi-Inclusive Deep Inelastic Scattering (SIDIS) using  $lp_\uparrow \rightarrow l'\pi X$  was reported by both the CLAS and the HERMES collaborations [1–4]. These large SSAs were also reported by the STAR and PHENIX collaborations [5–7] in pion production using a polarized proton beams at collider energies  $p_\uparrow p \rightarrow \pi X$ . Large SSAs are triggered by  $\mathcal{P}$ -odd contributions in the scattering amplitude that are not amenable to QCD perturbation theory.

The QCD vacuum supports large instanton-antinstanton fluctuations that are non-perturbative in nature and a natural source for  $\mathcal{P}$ -odd contributions. QCD instantons are hedgehog in color-spin, that makes them ideal for triggering large spin asymmetries [8–11]. Recently, we have shown that the one-instanton and one-antinstanton contributions to both  $lp_\uparrow \rightarrow l'\pi X$  and  $p_\uparrow p \rightarrow \pi X$  yield results that are consistent with the large measured asymmetries reported in the above experiments [12]. These  $\mathcal{P}$ -odd contributions are beyond the realm of factorization and provides a QCD based quantitative mechanism for the Sivers effect.

In this note we would like to argue that these  $\mathcal{P}$ -odd instanton contributions at the origin of the Sivers effect, may cause large pion azimuthal correlations in *unpolarized*  $pp$  scattering at the LHC. The fluctuations in the spin of the projectile and target correlate in event-by-event, causing  $\mathcal{P}$ -odd pion azimuthal correlations as we will detail below.

The organization of this note is as follows: we first revisit the SSA induced by a single instanton (antinstanton) contribution in polarized  $p_\uparrow p$  collisions [12]. We give a simple assessment of the  $\mathcal{P}$ -odd contributions with their pertinent probabilities of occurrence in unpolarized  $pp$  collisions. We use this assessment to evaluate the pion charge-dependent azimuthal correlations in  $pp$  collisions at the LHC. We extend our analysis to many independent and unpolarized  $pp$  collisions in one event. The  $\mathcal{P}$ -odd azimuthal charge correlations are found to deplete rapidly with the number of independent participants. We argue that this mechanism may still be at work in peripheral heavy-ion collisions as reported by STAR [13].

**2.  $pp$  Collisions** The unpolarized proton beam is an equal admixture of 6 proton polarizations along or against the 3 independent spatial directions. For unpolarized  $pp$  collisions this amounts to  $6 \times 6 = 36$  initial spin configurations of equal probability. We illustrate in Fig. 1 one of the equally probable collision configuration.

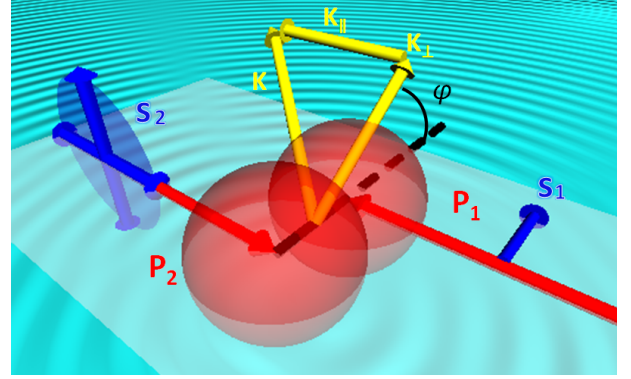


FIG. 1: Illustration of the reaction plane for 2 colliding protons.  $P_1$  carries a spin along the impact parameter, while  $P_2$  carries a spin orthogonal to it. The emitted pion carries transverse momentum  $K_\perp$  with azimuthal angle  $\phi$ .

The colliding protons carry momentum-spin assignments  $(P, S)_{1,2}$ . The reaction plane is defined by the longitudinal kinematics and the impact parameter. The emitted pion with momentum  $K$  projects to  $K_\perp$  onto the transverse plane, with azimuthal angle  $\phi$  with respect to the reaction plane or impact parameter.

Let  $P_1$  be the forward kinematical direction. At asymptotic  $\sqrt{s}$  (about 7 TeV at the LHC), the one-instanton induced asymmetries for forward ( $A_{\pi^\pm}^F$ ) and backward ( $A_{\pi^\pm}^B$ ) pion productions for the spin polarizations shown in Fig. 1 are readily derived using our analysis in [12],

$$A_{\pi^+}^F \approx \frac{\Delta u_s(x_1, Q^2)}{u(x_1, Q^2)} \frac{K_\perp}{4z} \Psi\left(\rho \frac{K_\perp}{z} \sqrt{\frac{x_1 z}{x_F}}\right) \left(1 + \frac{x_1 z}{x_F}\right) \sin \phi \quad (1)$$

$$A_{\pi^-}^F \approx \frac{\Delta d_s(x_1, Q^2)}{d(x_1, Q^2)} \frac{K_\perp}{4z} \Psi\left(\rho \frac{K_\perp}{z} \sqrt{\frac{x_1 z}{x_F}}\right) \left(1 + \frac{x_1 z}{x_F}\right) \sin \phi \quad (2)$$

$$A_{\pi^+}^B = A_{\pi^-}^B = - \frac{\Delta u_s(x_1, Q^2) + \Delta d_s(x_1, Q^2)}{u(x_1, Q^2) + d(x_1, Q^2)} \times \frac{K_\perp}{4z} \Psi\left(\rho \frac{K_\perp}{z} \sqrt{\frac{x_2 z}{|x_F|}}\right) \left(1 + \frac{x_2 z}{|x_F|}\right) \sin \phi \quad (3)$$

with

$$\Psi(a) \equiv \frac{2\pi^2 \rho^4}{\lambda a^2} \left[ \frac{4}{a^2} - \frac{4}{3} a K_1(a) - 2K_2(a) + \frac{1}{3} \right] \quad (4)$$

$\rho$  is the instanton size and  $\lambda$  the mean quark zero-mode virtuality. In the QCD vacuum  $\rho \approx 1/3$  fm [14, 15]. The mean instanton quark zero mode virtuality is tied to the light quark condensate. For two flavors the condensate  $\chi_{uu} \approx (200 \text{ MeV})^3$ , so that  $\bar{\lambda} \approx 1/(0.2 \text{ GeV})^3$ .

The spin polarized distribution functions  $\Delta u_s(x, Q^2)$  and  $\Delta d_s(x, Q^2)$  for the valence up and down quarks will be borrowed from experiments [16, 17]. Specifically,  $\Delta u_s(x, Q^2)/u(x, Q^2) = 0.959 - 0.588(1 - x^{1.048})$ ,  $\Delta d_s(x, Q^2)/d(x, Q^2) = -0.773 + 0.478(1 - x^{1.243})$  and  $d(x, Q^2)/u(x, Q^2) = 0.624(1 - x)$ .

$x_F$  is the pion longitudinal momentum fraction  $K_{\parallel} = x_F \sqrt{s}/2$ , with  $x_F > 0$  for forward and  $x_F < 0$  for backward production.  $x_{1,2}$  are factorization parameters for  $P_{1,2}$  and  $z$  the fragmentation parameter.  $\langle x_1 \rangle$  is large and  $\langle x_2 \rangle$  is small for forward pion productions at large  $\langle x_F \rangle$ , while  $\langle x_1 \rangle$  is small and  $\langle x_2 \rangle$  is large for large negative  $\langle x_F \rangle$  [12]. As the fluctuations in the differential cross section to follow is mainly due to large SSA effects (large  $x_F$ ), we will set  $\langle x_1 \rangle = 0.9$  and  $\langle x_2 \rangle = 0.1$  for forward pion production, and  $\langle x_1 \rangle = 0.1$  and  $\langle x_2 \rangle = 0.9$  for backward pion productions. For simplicity, we will set  $\langle x_F \rangle = \pm 0.5$  and  $\langle z \rangle = 0.5$ .

For the LHC kinematics we will choose  $\langle K_{\perp} \rangle = 3 \text{ GeV}$ . Combining both forward (1-2) and backward pion productions (3), we can make the  $\mathcal{P}$ -odd charged pion asymmetries explicit. Specifically,

$$\begin{aligned} A_{\pi^+} &\approx +2 \times 0.0207 \sin \phi \\ A_{\pi^-} &\approx -2 \times 0.0178 \sin \phi \end{aligned} \quad (5)$$

If we recall that the  $\mathcal{P}$ -odd asymmetry in the azimuthal pion multiplicity is parametrized as [13]

$$\frac{dN_{\alpha}}{d\phi} \sim 1 + 2v_{\alpha} \sin \phi \quad (6)$$

we conclude by comparison with (5) that:  $v_{\pi^+} = 0.0207$  and  $v_{\pi^-} = -0.0178$  for the 4 equally probable collisions illustrated in Fig. 1. For comparison, we illustrate in Fig. 2 a collision with a different spin arrangement. In this case both  $S_{1,2}$  are in the reaction plane but opposite to each other. A rerun of the same arguments yield:  $v_{\pi^+} = 0.0414$  and  $v_{\pi^-} = -0.0356$ .

Since the collision with  $P_1$  and  $P_2$  is symmetric, the corresponding probability for the 4 collisions illustrated in Fig. 1 is:  $2 \times 4/36$ . The probability for the 1 collision illustrated in Fig. 2 is  $1/36$ . The interchange  $1 \leftrightarrow 2$  in the latter is redundant. Table I summarizes the pertinent charged pion asymmetries with their probability weights for equally likely collisions.

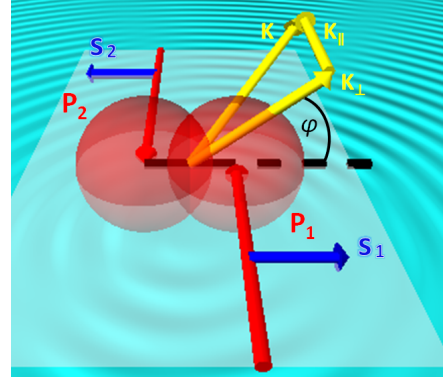


FIG. 2: Same as Fig. 1 but with now the two spins  $S_{1,2}$  in the reaction plane and opposite to each other.

Probability	$v_{\pi^+}$	$v_{\pi^-}$
1/36	0.0414	-0.0356
1/36	-0.0414	0.0356
2/9	0.0207	-0.0178
2/9	-0.0207	0.0178
1/2	0	0

TABLE I:  $\mathcal{P}$ -odd asymmetry factors in charged pion productions in  $pp$  collisions with a transverse pion momentum  $\langle K_{\perp} \rangle = 3 \text{ GeV}$  and instanton size  $\langle \rho \rangle = 1/3 \text{ fm}$ .

We note that on average the  $\mathcal{P}$ -odd asymmetries  $\langle v_{\pi^{\pm}} \rangle = 0$  vanish when averaged over all  $pp$  collisions. However, their fluctuations or correlations do not. Indeed, the like-charge azimuthal pion correlations are readily constructed from Table I,

$$\begin{aligned} \langle v_{\pi^+} v_{\pi^+} \rangle &= \frac{2}{36} \times 0.0414^2 + \frac{4}{9} \times 0.0207^2 = 0.286 \times 10^{-3} \\ \langle v_{\pi^-} v_{\pi^-} \rangle &= \frac{2}{36} \times 0.0356^2 + \frac{4}{9} \times 0.0178^2 = 0.211 \times 10^{-3} \end{aligned} \quad (7)$$

and similarly for the unlike-charge azimuthal pion correlations

$$\begin{aligned} \langle v_{\pi^+} v_{\pi^-} \rangle &= -\frac{2}{36} \times 0.0414 \times 0.0356 - \frac{4}{9} \times 0.0207 \times 0.0178 \\ &= -0.246 \times 10^{-3} \end{aligned} \quad (8)$$

In Table II we show our results for the  $\mathcal{P}$ -odd and charge-dependent azimuthal pion correlations for unpolarized  $pp$  collisions at the LHC. Since our results depend on the mean value of the transverse pion momentum  $\langle K_{\perp} \rangle$  and the size of the instanton  $\langle \rho \rangle$ , Table II shows the results for a reasonable choice range. We note that our predictions are robust against these parameter changes.

**3. AA Collisions.** The charge-dependent azimuthal correlations in unpolarized  $pp$  collisions as detailed before may survive in peripheral heavy-ion collisions both

$\rho$ fm	$K_{\perp}$ GeV	1/36		1/36		2/9		2/9		1/2	$\langle v_{\pi^+} v_{\pi^+} \rangle$ $\times 10^{-3}$	$\langle v_{\pi^-} v_{\pi^-} \rangle$ $\times 10^{-3}$	$\langle v_{\pi^+} v_{\pi^-} \rangle$ $\times 10^{-3}$
		$v_{\pi^+}$	$v_{\pi^-}$	$v_{\pi^+}$	$v_{\pi^-}$	$v_{\pi^+}$	$v_{\pi^-}$	$v_{\pi^+}$	$v_{\pi^-}$	$v_{\pi^+} (v_{\pi^-})$			
1/3	3	0.0414	-0.0356	-0.0414	0.0356	0.0207	-0.0178	-0.0207	0.0178	0	0.286	0.211	-0.246
1/3	4	0.0298	-0.0256	-0.0298	0.0256	0.0149	-0.0128	-0.0149	0.0128	0	0.148	0.109	-0.127
1/3	5	0.0224	-0.0193	-0.0224	0.0193	0.0112	-0.0097	-0.0112	0.0097	0	0.084	0.062	-0.072
1/2	3	0.0866	-0.0746	-0.0866	0.0746	0.0433	-0.0373	-0.0433	0.0373	0	1.250	0.928	-1.077
1/2	4	0.0592	-0.0514	-0.0592	0.0514	0.0296	-0.0257	-0.0296	0.0257	0	0.584	0.440	-0.507
1/2	5	0.0441	-0.0386	-0.0441	0.0386	0.0221	-0.0193	-0.0221	0.0193	0	0.324	0.248	-0.284
2/3	3	0.1400	-0.1217	-0.1400	0.1217	0.0700	-0.0609	-0.0700	0.0609	0	3.267	2.468	-2.840
2/3	4	0.0962	-0.0844	-0.0962	0.0844	0.0481	-0.0422	-0.0481	0.0422	0	1.542	1.187	-1.353
2/3	5	0.0731	-0.0645	-0.0731	0.0645	0.0366	-0.0323	-0.0366	0.0323	0	0.891	0.693	-0.786

TABLE II: Expected charge-dependent azimuthal correlations in unpolarized  $pp$  collisions.

n	$\langle v_{\pi^+} v_{\pi^+} \rangle$ $\times 10^{-3}$	$\langle v_{\pi^-} v_{\pi^-} \rangle$ $\times 10^{-3}$	$\langle v_{\pi^+} v_{\pi^-} \rangle$ $\times 10^{-3}$
1	0.817	0.798	-0.807
2	1.074	1.050	-1.061
3	0.890	0.870	-0.880
4	0.598	0.584	-0.591
5	0.358	0.350	-0.354
6	0.200	0.195	-0.197
7	0.107	0.104	-0.106
8	0.056	0.054	-0.055
9	0.028	0.028	-0.028
10	0.014	0.014	-0.014

TABLE III: Expected charge-dependent azimuthal correlations of  $n$  independent hard  $pp$  collisions with  $\langle K_{\perp} \rangle = 1$  GeV and  $\langle \rho \rangle = 1/3$  fm in one event. See text.

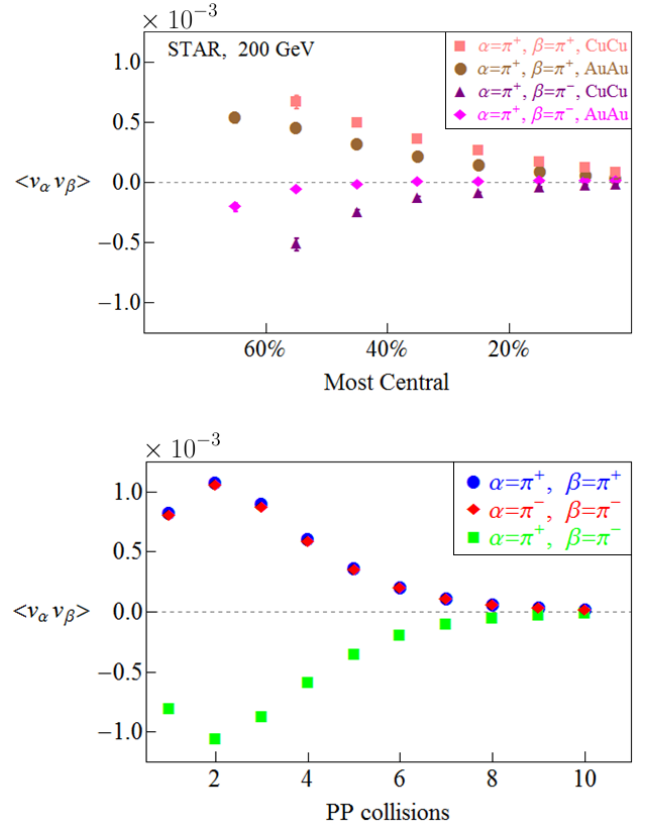
Probability	$v_{\pi^+}$	$v_{\pi^-}$
1/36	0.0700	-0.0692
1/36	-0.0700	0.0692
2/9	0.0350	-0.0346
2/9	-0.0350	0.0346
1/2	0	0

TABLE IV:  $\mathcal{P}$ -odd asymmetry factors in charged pion productions in  $pp$  with  $\langle K_{\perp} \rangle = 1$  GeV and  $\langle \rho \rangle = 1/3$  fm.

at RHIC and LHC. To estimate this effect, consider  $n$  independent hard  $pp$  collisions in a heavy ion event. In Table III we tabulate our estimates for like and unlike charged pion azimuthal correlations as a function of the number of  $n$ . The correlations dwindle with increasing  $n$  because of the rapid increase in the number of spin combinatorics and therefore the smallness of the weight factors in the truly correlated spin arrangements. Table III was derived using  $\langle K_{\perp} \rangle = 1$  GeV and  $\rho \approx 1/3$  fm for which Table IV for  $pp$  is pertinent. We recall that in the STAR's experiment [13],  $\langle K_{\perp} \rangle$  ranges from 0.15 GeV to 2 GeV.

Fig. 3 (lower) displays the  $\mathcal{P}$ -odd like and unlike charged pion correlations as a function of the number of hard  $pp$  collisions, as recorded in Table III. Similar correlations were reported by the STAR collaboration at RHIC as a function of centrality. For illustrative comparison we display their results in Fig. 3 (upper). It is amus-

ing to note that for the very peripheral events at RHIC, the azimuthal correlations are of the same order of magnitude as the the ones we estimated from our instanton induced Siverts effect. We suggest that this mechanism may still be at work in peripheral heavy ion collisions both at RHIC and LHC.

FIG. 3: Upper figure — experimental results of charge-dependent azimuthal correlations in  $Au + Au$  and  $Cu + Cu$  collisions at  $\sqrt{s} = 200$  GeV [13]. Lower figure — expected charge-dependent azimuthal correlations of  $n$  independent hard  $pp$  collisions in one event.

**4. Conclusions.** Large  $\mathcal{P}$ -odd instanton contributions to the Siverts effect in polarized  $pp$  experiments may contribute substantially to  $\mathcal{P}$ -odd azimuthal correlations

in *unpolarized*  $pp$  collisions with high pion multiplicity such as  $pp$  collisions at LHC. We have provided simple estimates for the like and unlike pion correlations at LHC. Their future measurements will provide more constraints on our understanding of polarized  $pp$  experiments. We have suggested that the Siverson effect may still contribute to the recently reported  $\mathcal{P}$ -odd azimuthal pion correlations by the STAR collaboration [13]. We noted that these effects deplete rapidly with the number of independent hard  $pp$  collisions unless more nuclear

spin correlations are retained in the shattering stage of the heavy ion collision. We note that  $\mathcal{P}$ -odd Collins effects were recently argued in the context of the quark fragmentation function [18], that maybe complementary to our arguments.

**Acknowledgements.** This work was supported in parts by the US-DOE grant DE-FG-88ER40388.

- 
- [1] HERMES Collaboration, A. Airapetian *et al.*, Phys. Rev. Lett **84**, 4047 (2000).
  - [2] HERMES Collaboration, A. Airapetian *et al.*, Phys. Rev. Lett **94**, 012002 (2005).
  - [3] HERMES Collaboration, A. Airapetian *et al.*, Phys. Rev. Lett **103**, 152002 (2009).
  - [4] CLASS Collaboration, H. Avakian *et al.*, Phys. Rev. Lett **105**, 262002 (2010).
  - [5] FNAL E704 Collaboration, D. L. Adams *et al.*, Phys. Lett. B **264**, 462 (1991).
  - [6] PHENIX Collaboration, Mickey Chiu, arXiv: 0701031 [nucl-ex].
  - [7] STAR Collaboration, B. I. Abelev *et al.*, Phys. Rev. Lett **101**, 222001 (2008).
  - [8] M. Anselmino and S. Forte, Phys. Rev. Lett. **71**, 223 (1993) [hep-ph/9211221].
  - [9] N. I. Kochelev, JETP Lett. **72**, 481 (2000) [Pisma Zh. Eksp. Teor. Fiz. **72**, 691 (2000)] [hep-ph/9905497].
  - [10] D. Ostrovsky and E. V. Shuryak, Phys. Rev. D **78**, 014001 (2005).
  - [11] A. E. Dorokhov, N. I. Kochelev and W. D. Nowak, Phys. Part. Nucl. Lett **6**, 440 (2009).
  - [12] Y. Qian and I. Zahed, arXiv:1112.4552 [hep-ph].
  - [13] STAR Collaboration, B. I. Abelev *et al.*, Phys. Rev. C **81**, 54908 (2010).
  - [14] T. Schafer and E. V. Shuryak, Rev. Mod. Phys **70**, 323 (1998).
  - [15] M. A. Nowak, M. Rho and I. Zahed, "Chiral Nuclear Dynamics", World Scientific (1996).
  - [16] M. Hirai, S. Kumano, and N. Saito, Phys. Rev. D **74**, 014015 (2006).
  - [17] M. Gluck, E. Reya, and A. Vogt, Eur. Phys. J.C **5**, 461 (1998).
  - [18] Z. -B. Kang and D. E. Kharzeev, Phys. Rev. Lett. **106**, 042001 (2011) [arXiv:1006.2132 [hep-ph]].